THE NATIONAL IGNITION FACILITY PROJECT

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Introduction

The Secretary of the U.S. Department of Energy (DOE) commissioned a Conceptual Design Report (CDR) for the National Ignition Facility (NIF) in January 1993 as part of a Key Decision Zero (KD0), Justification of Mission Need. Motivated by the progress to date by the Inertial Confinement Fusion (ICF) program in meeting the Nova Technical Contract[1] goals established by the National Academy of Sciences in 1989, the Secretary requested a design using a solid-state laser driver operating at the third harmonic (0.35 µm) of neodymium (Nd) glass. The participating ICF laboratories signed a Memorandum of Agreement in August 1993, and established a Project organization, including a technical team from the Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and the Laboratory for Laser Energetics at the University of Rochester. Since then, we completed the NIF conceptual design, based on standard construction at a generic DOE Defense Program's site, and issued a 7,000-page, 27-volume CDR in May 1994.[2] Over the course of the conceptual design study, several other key documents were generated, including a Facilities Requirements Document, a Conceptual Design Scope and Plan, a Target Physics Design Document, a Laser Design Cost Basis Document, a Functional Requirements Document, an Experimental Plan for Indirect Drive Ignition, and a Preliminary Hazards Analysis (PHA) Document. DOE used the PHA to categorize the NIF as a low-hazard, non-nuclear facility.

Figure 1 shows the NIF conceptual design, which was exhaustively reviewed during the past year. A subcommittee of the Inertial Confinement Fusion Advisory Committee (ICFAC) reviewed and endorsed the laser performance of the 40-cm aperture, 192-beam multipass architecture in April 1994. The full ICFAC reviewed target design and ignition scaling in May 1994 and recommended DOE approval of the preliminary design phase of the Project. Subcontractors to DOE Defense Programs scrutinized the engineering design during the design period, while an Independent Cost Estimator team commissioned by DOE Field Management intensively reviewed and validated the cost and schedule in March and April 1994. The performance, cost, and schedule represented in the CDR were formally submitted in June 1994 in a Project Data Sheet for inclusion in the FY 1996 DOE funding cycle.

On October 21, 1994 the Secretary of Energy issued a Key Decision One (KD1) for the NIF, which approved the Project and authorized DOE to request Office of Management and Budget–approval for congressional line-item FY 1996 NIF funding for preliminary engineering design and for National Environmental Policy Act activities. In addition, the Secretary declared Livermore as the preferred site for constructing the NIF. In February 1995, the NIF Project was formally submitted to Congress as part of the President's FY 1996 budget. If funded as planned, the Project will cost approximately $1.1 billion and will be completed at the end of FY 2002.

This article presents an overview of the NIF Project.

NIF Design Criteria

The identified laser power and energy operating regimes for indirect-drive fusion ignition targets are displayed in Fig. 2 and are the basis for the primary

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design criteria for the facility (Table 1). Each point on the operating map corresponds to a different temporal pulse shape, typically one with a relatively long foot-pulse (10–20 ns), followed by a short peak-pulse (2–8 ns) having a high contrast ratio (25–100:1). In the high-power, short-temporal-pulse region, performance is limited by laser–plasma instabilities, while in the low-power, long-temporal-pulse region, performance is limited by hydrodynamic instabilities.

The baseline target, shown in Fig. 3, requires a laser system that routinely delivers 500 TW / 1.8 MJ at 0.35 µm in a 50:1 contrast ratio pulse through a 500-µm spot at the laser entrance hole of the target hohlraum with a positioning accuracy of 50 µm. Each beam must achieve a power balance of approximately 8% rms (over any 2-ns interval) with respect to a reference value. As summarized by the design rules in Table 2, symmetrical implosion of the capsule requires two-sided target irradiation with two cones per side, each having an outer cone:inner cone laser power ratio of 2:1, and at least eight-fold azimuthal irradiation symmetry. The cone angles, nominally at 53° (outer) and 27° (inner), and laser power ratio are chosen to maintain time-dependent symmetry of the x-ray drive seen by the imploding capsule.

To avoid laser–plasma instabilities, such as filamentation and stimulated scattering, the baseline indirect-drive target hohlraum requires laser spatial beam smoothing using phase plates and laser temporal smoothing with a combination of four beams at different center wavelengths, each separated by 3.3 Å (3.3×10^{-4} µm). This separation is set by a beam-smoothing requirement on the motion of the kinoform-induced speckle pattern at the target focus.

As a consequence of these symmetry design rules, the laser system must deliver at least 192 beams to the target chamber. A laser system designed to meet these criteria has a power and energy safety margin of approximately two for achieving ignition, as indicated in Fig. 2. These laser system requirements, optimized

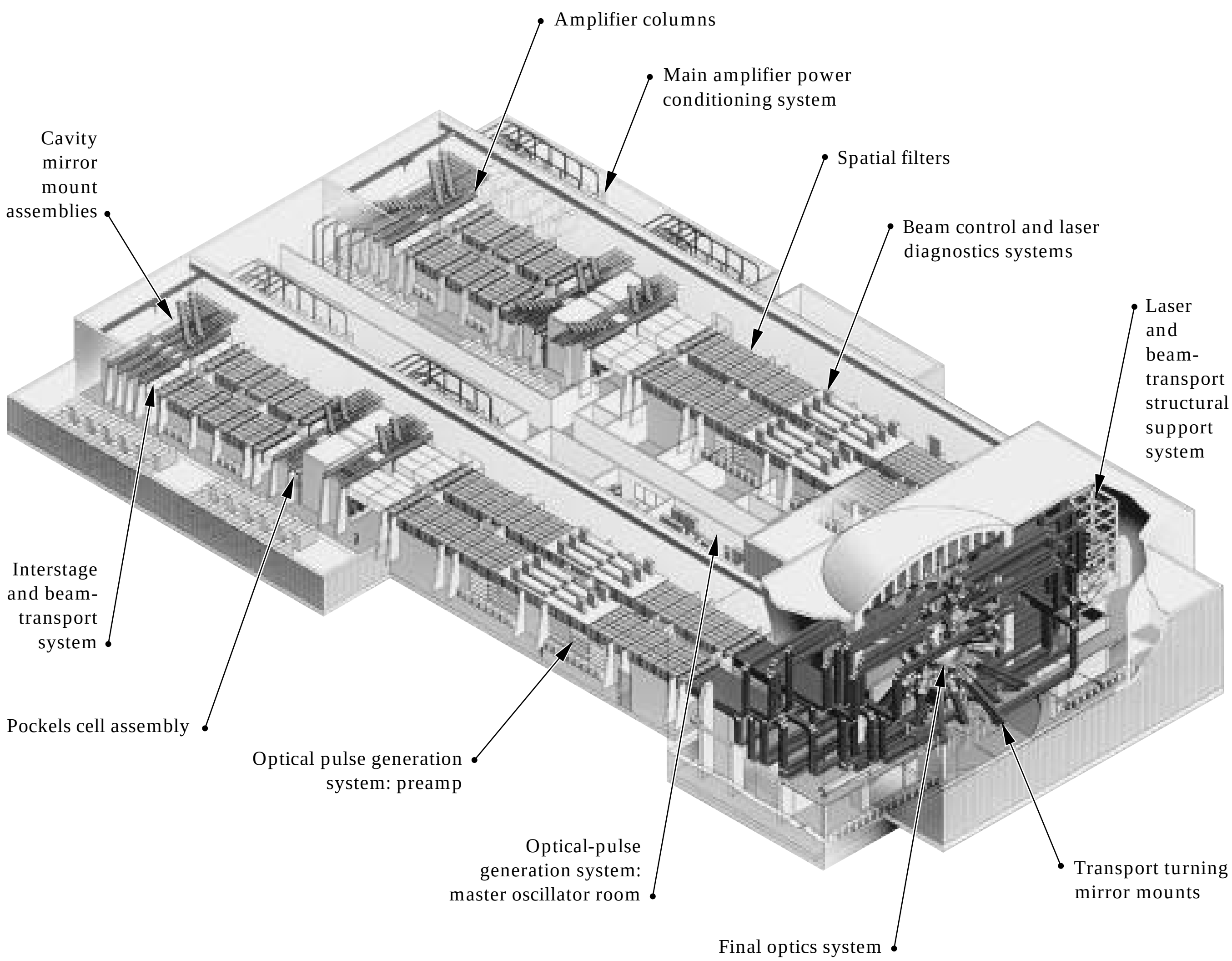


FIGURE 1. The NIF overview. The NIF will be a low-hazard, non-nuclear facility. (40-00-0294-0498Zpb03)

for indirect-drive ignition targets, are consistent with those proposed for direct-drive ignition targets.

The primary criteria for the NIF systems given in Table 1 represent a small subset of the functional requirements for the facility, which include other mission-related and lifecycle requirements for the laser, experimental area, radiation-confinement systems, building and structural systems, safety systems, environmental protection systems, and safeguard and security systems. The NIF was designed for a generic site and is consistent with all relevant orders, codes, and standards. The U-shaped building configuration satisfies a key functional requirement: providing for the future addition of a second large target chamber to accommodate special requirements of other communities, such as for weapons effect tests, with minimal interruptions to system operations. Preliminary analysis

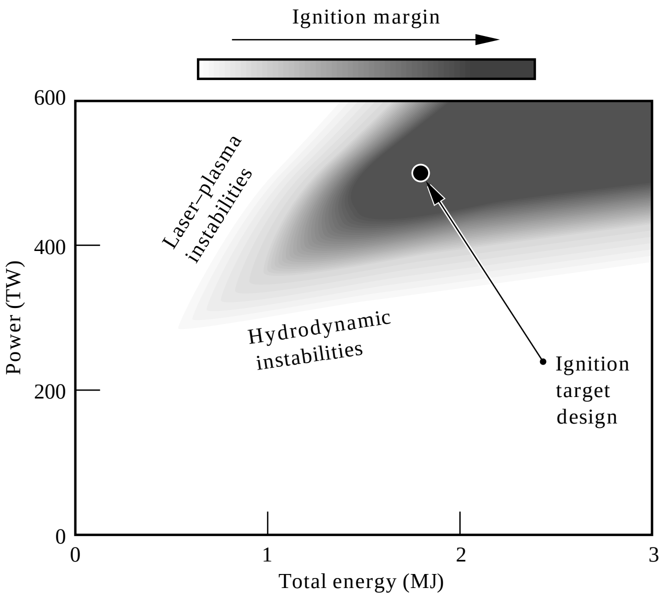


FIGURE 2. The indirect-drive target operating regime in laser power-energy space at 0.35 µm. The operating regime is constrained by laser–plasma instabilities and hydrodynamic instabilities. Each point on the plane corresponds to a unique two-step temporal pulse. The baseline design at 500 TW / 1.8 MJ has approximately a factor of two safety margin for ignition. This energy and power safety margin above threshold provides room to trade off asymmetry, laser–plasma instabilities, and other uncertainties. (50-05-0494-1803pb02)

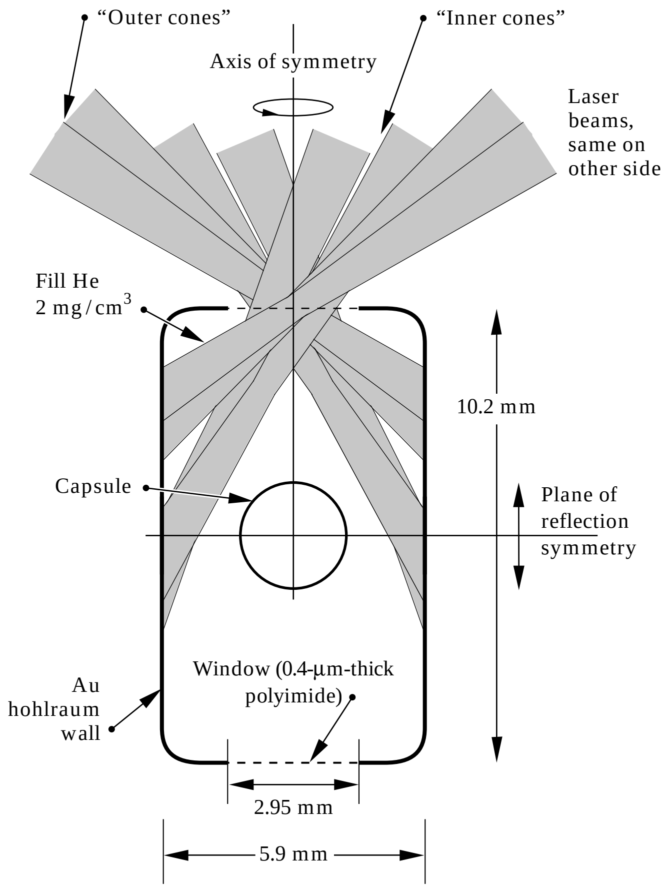


FIGURE 3. A baseline NIF target was used to establish design criteria for the facility. The outer cones enter at 57° and 48°, with a 500-µm best focus at the entrance hole (f/8). The inner cones enter at 23° and 32°, with a 500-µm best focus ~3 mm inside the hohlraum (f/8). (40-00-0294-0596Apb01)

TABLE 1. Primary criteria for the National Ignition Facility.

Laser pulse energy	1.8 MJ
Laser pulse peak power	500 TW
Laser pulse wavelength	0.35 µm
Beamlet power balance	<8% rms over 2 ns
Beamlet pointing accuracy	<50 µm
ICF target compatibility	Cryogenic and non-cryogenic
Annual number of shots with fusion yield	100 with yield 1 kJ–100 kJ
	35 with yield 100 kJ–5 MJ
	10 with yield 5 MJ–20 MJ
Maximum credible DT fusion yield	45 MJ
Classification level of experiments	Classified and unclassified

TABLE 2. Minimum number of 192 beams delivered to ignition target is determined by implosion symmetry requirements.

Symmetry	Beam multiplier	Notes
Time dependent hydrodynamic	3	Outer cone at ~53° at 2× energy / power
		Inner cone at ~27° at 1× energy / power
Azimuthal	≥8 (or 8, 9, 10…)	Number of inner-cone laser spots on hohlraum wall
Reflection	2	
Beam smoothing	4	Smoothing by multiple apertures / colors
Required number of beams	≥192 (or 192, 216, 240…)	

has shown that a modest upgrade of the currently designed NIF target area and target chamber system would accommodate direct-drive ignition target experiments without impacting the indirect-drive mission.

Laser System Design

The Nd:glass laser system must provide at least 632 TW / 3.3 MJ in a 5.1-ns pulse at 1.053 µm to account for modest beam transport losses, and energy and power conversion efficiencies of 60% and 85%, respectively. Figure 4 shows a schematic of one NIF beamline. It uses a four-pass architecture with a large-aperture optical switch consisting of a plasma-electrode Pockels cell and polarizer combination.

The laser chain in this beamline was designed using the CHAINOP family of numerical codes that model the performance and cost of high-power solid-state ICF laser systems. These codes vary a number of design parameters to maximize laser output per unit cost, while remaining within a set of constraints. The constraints include fluence maxima, nonlinear effects, and pulse distortion. CHAINOP contains several analytical models that simulate the optical pumping process, the propagation of the laser beam through the system (including gain, loss, diffraction, and nonlinear optical effects), frequency conversion, and cost. This design procedure is excellent for cost scaling and system trade-off studies, but does not suffice for predicting detailed performance, which requires analysis with a suite of nonlinear physical optics codes, or determining project costs, which are estimated using a detailed engineering design and a rigorous item by item or "bottom-up" costing described later in this article.

The laser chain used in the CDR as the baseline for estimating NIF system cost and performance has a hard aperture of 40×40 cm^2. The amplifiers contain 19 Nd-doped glass laser slabs arranged in a 9-5-5 configuration as shown in Fig. 4. Each Brewster-angled slab is 3.4 cm thick. Figure 5 shows the 1.053-µm performance of this laser chain. At the 5.1-ns design point each laser chain should generate 3.9 TW / 20.5 kJ. Because only 162 beams are required to achieve the performance criteria, a 192-beam system has a design margin of greater than 15%. A prototype beamline, called Beamlet, is undergoing tests at LLNL to demonstrate NIF performance projections using the large-aperture optical switch. Variations of a NIF design with reduced-aperture switches have comparable performance projections when optimized.

The NIF design incorporates 4-high $\times$ 12-wide arrays of laser beams as shown in Figure 1. The design is more compact than previous laser fusion systems, increasing

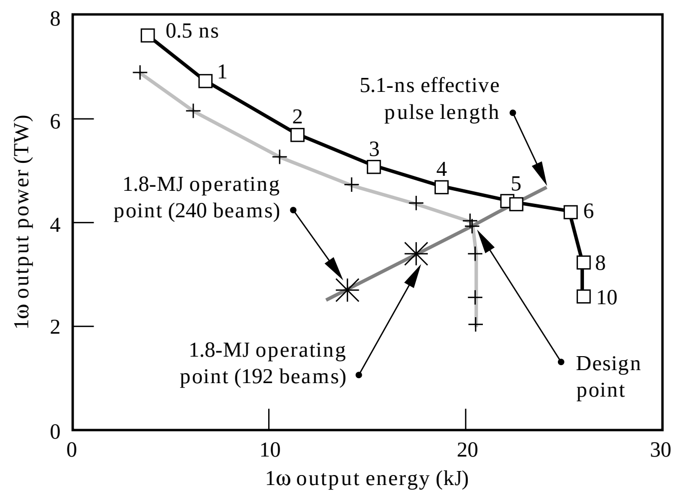


FIGURE 5. The 1.05-µm power / energy performance as a function of pulse length for the 9-5-5 configuration (shown in Fig. 4). The gray line shows the baseline performance (nominal-gain and -loss case). The black line illustrates the performance with line-center gain and with improved optical transmission of the laser glass and optical switch. For a 5.1-ns effective pulse length, determined by the NIF temporal pulse shape, the maximum gray-line performance of 20 kJ sets the number of required beams at 162. This would produce 3.3 MJ of 1.05 µm light and would deliver 1.8 MJ of 0.35-µm light to the laser entrance hole of the target hohlraum. Changing the system total from 162 to 192 (240) beams would provide an 18% (48%) laser design margin to meet the target hohlraum requirements. (40-00-0394-1378pb01)

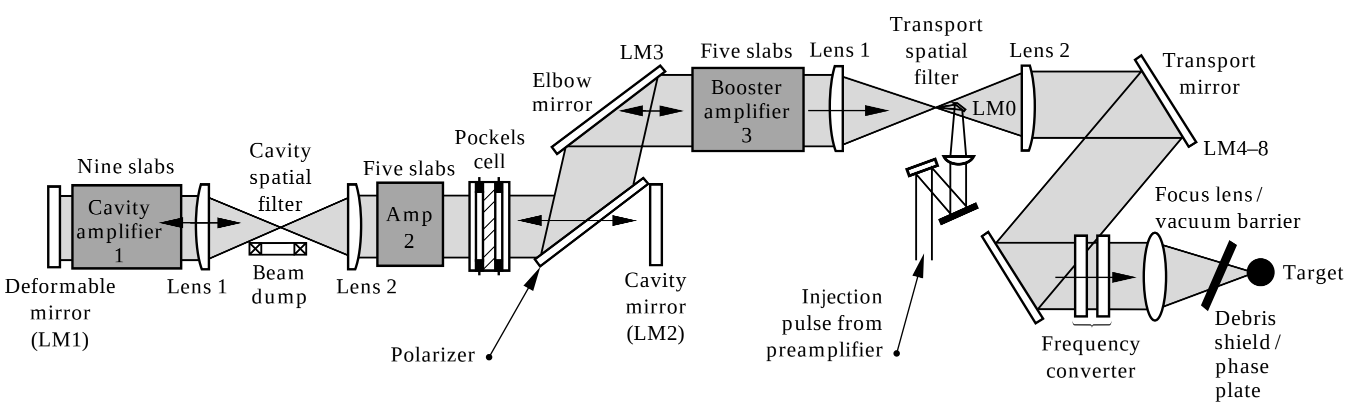


FIGURE 4. A schematic of one beamline of the NIF laser from pulse injection to final focus on target. (40-00-0394-0789Apb02)

overall electrical and optical efficiency while simultaneously reducing system size and cost. The optical-pulse generation system provides individually controlled input pulses from one of four tunable fiber oscillators and an integrated optics network located in the master oscillator room (MOR). The outputs from the MOR are delivered on single-mode polarization preserving fibers to each of 192 preamplifiers. These stand-alone packages, located beneath the transport spatial filters, provide individual power balance capability for each of the 192 beams. The output beams from the preamplifiers are injected into the far-field pinholes of the transport spatial filters, passed through the boost-amplifier stages, the optical switch assemblies, and then captured inside the multipass cavities. The flash lamps located in the amplifier enclosures that uniformly pump the glass laser slabs are energized with approximately 260 MJ of electrical energy from a modular bank of thin film, metallized dielectric capacitors. After four passes through the cavity amplifiers, the pulses are switched out of the multipass cavity, further amplified by the boost stage, and then transported to the target chamber. The laser arrangement allows for top and bottom access to the amplifiers and the optical switch arrays. The pulsed power is transmitted to the amplifiers overhead with large, 30-cm-diam, coaxial conductors. The space below the amplifiers allows access for assembly and maintenance of any four-high amplifier column.

Wavefront aberrations resulting from the long-term thermal cooling of the glass laser slabs ultimately limit the shot rate of the laser system. The NIF is currently designed to achieve about 700 full-system performance shots / year. A novel feature of the current design is the use of deformable mirrors in place of the end cavity mirrors (see Fig. 4) to correct for static and pump-induced short-term wavefront aberrations, which will allow for higher shot rates. It is expected that through continued engineering design of the wavefront-correction and cooling systems, the laser shot rate will increase substantially. This is consistent with engineering improvements on all previous ICF glass laser systems, including Nova, which has had its shot rate increase by a factor of six since operations began in 1985.

Target Area Design

Figure 6 shows a cutaway view of the switchyard and target area. The 192 laser beams are optically relayed via the transport spatial filters in 48 2×2 groupings to the final optics assemblies. The beams are constrained to only *s*- and *p*-polarized reflections in the optical switchyard and target areas so that they maintain linear

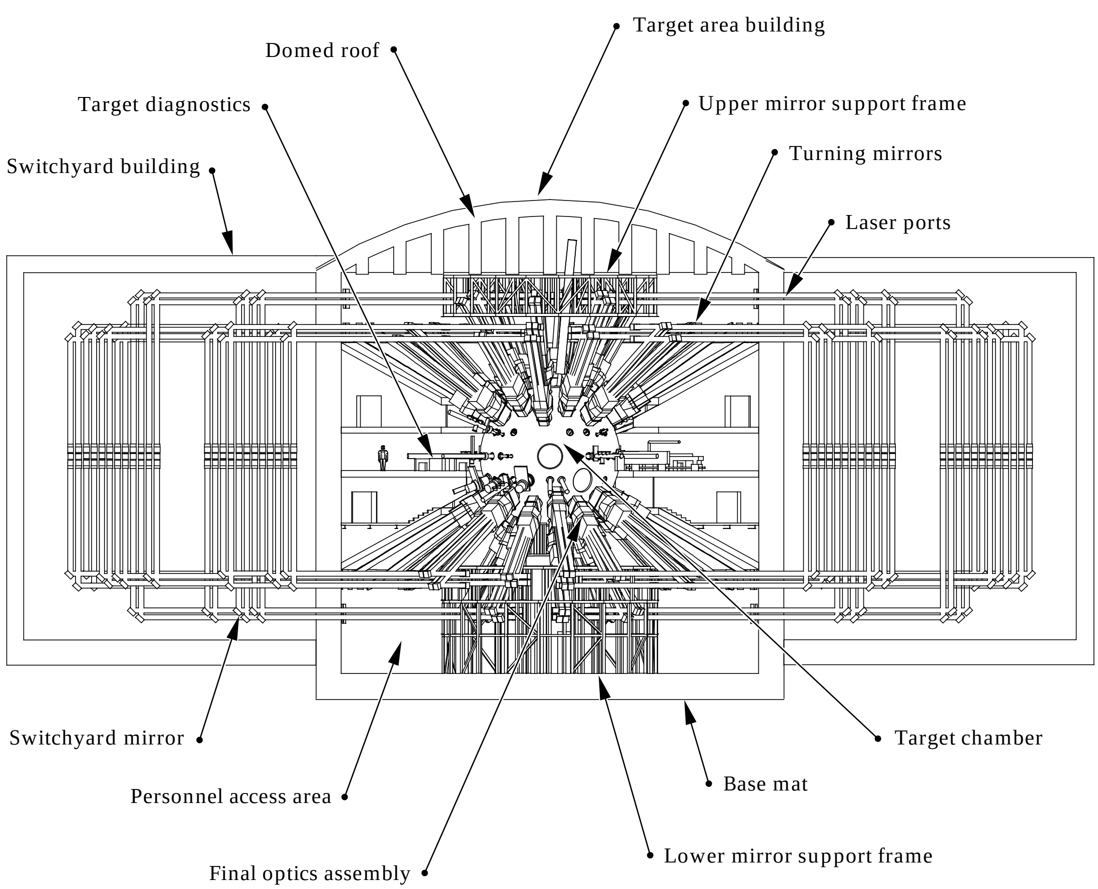


FIGURE 6. A cutaway view of the NIF target area showing major subsystems. (40-00-0394-1030pb01)

polarization and radial symmetry with respect to the cylindrical axis on the hohlraum. Consequently, there is complete azimuthal symmetry. The 48 final optics assemblies (Fig. 7) are positioned on the 53° outer cones (16 assemblies) and 27° inner cones (8 assemblies) at the top and on the bottom of the target chamber. At the chamber each 2×2 grouping is converted to 0.35 µm by a Type I (potassium dihydrogen phosphate, or KDP) / Type II (deuterated KDP, or KD*P) crystal array in the final optics assembly. The final optics assemblies mount to the exterior of the chamber, and also provide 2×2 lens arrays for focusing the light onto the target and 2×2 debris shield arrays for protecting the lenses from target shrapnel. (The debris shields also contain the kinoform phase plates.) Each beam in every 2×2 grouping can be operated at a different center wavelength to provide the requisite laser temporal beam smoothing. The final optics assemblies are offset from the nominal cone angles by ±4° to provide isolation between opposing beamlines.

The target chamber is housed in a reinforced-concrete building with three separate operational areas (see Fig. 6). The upper and lower pole regions of the target chamber house the final optics and turning mirrors in a class 1000 clean room. Personnel access to these areas will be limited to preserve cleanliness levels. The cantilevered floor sections of the building provide a separation of the clean-room enclosures at the polar regions from the equatorial target diagnostics area. This horizontal, planar architecture simplifies the design of the access structures required to service the optical components and target diagnostics.

The NIF baseline target chamber is a 10-cm-thick by 10-m internal-diam spherical Al shell designed to

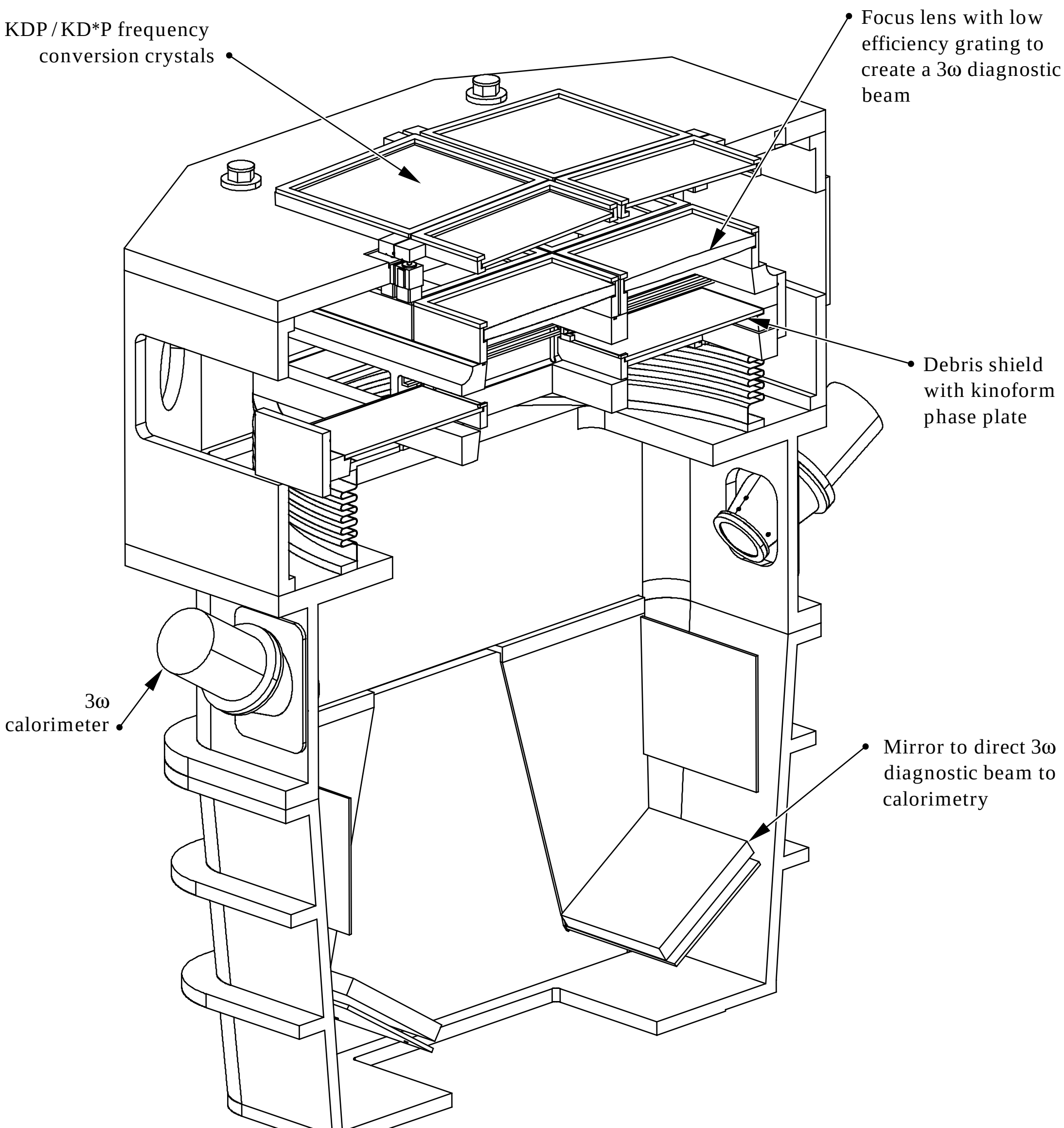


FIGURE 7. The final optics assembly has multiple functions: Frequency conversion, focusing, spatial smoothing, optics protection, 1ω / 2ω dispersion, 3ω calorimetry, and vacuum interface. (40-00-0294-0600Bpb01)

accommodate the suite of x-ray and neutron diagnostics required to measure the performance of targets that can achieve ignition. The Al wall provides the vacuum barrier and mounting surfaces for the first-wall panels, which protect the Al from soft x rays and shrapnel. The unconverted laser light hitting the opposite wall is absorbed by other panels offset from the opposing beam port. The exterior of the chamber is encased in 40 cm of concrete to provide neutron shielding. The chamber is supported vertically by a hollow concrete pedestal and horizontally by radial joints connected to the cantilevered floor. The target area building, chamber, and auxiliary systems are designed to handle 145 shots / year of yields up to 20 MJ as shown in Table 1.

Recent engineering analyses and target physics calculations show that the baseline design can be easily modified, as illustrated in Fig. 8, to incorporate a direct-drive ignition capability, further broadening the utility of the facility.

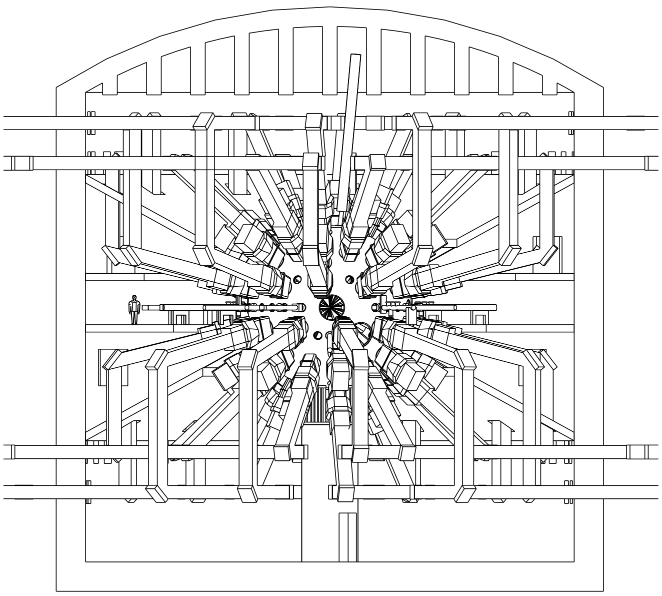


FIGURE 8. Implementation of direct drive requires that 24 of the 48 beams be repositioned. This can be accomplished easily using the NIF optical system design. Compare to Fig. 6. (40-00-0694-2750pb01)

NIF Project Schedule

The summary schedule shown in Fig. 9 illustrates the sequence of events leading to NIF operations in October 2002. This overall schedule assumes the NIF Project is initiated by line-item funding in FY 1996 consistent with a KD1. A more detailed integrated Project schedule (not shown) reveals the critical path that affects the Project duration. The major NIF critical path consists of design, site selection, design and construction of the laser and target areas building, laser and other special equipment installation, completion of the acceptance test procedures, and start-up. Construction completion, equipment installation, and start-up are overlapped to shorten the critical path within limits of a practical funding profile. The release of design, construction, procurement, and operating funds is constrained by the DOE Key Decision (KD1 through KD4) process.

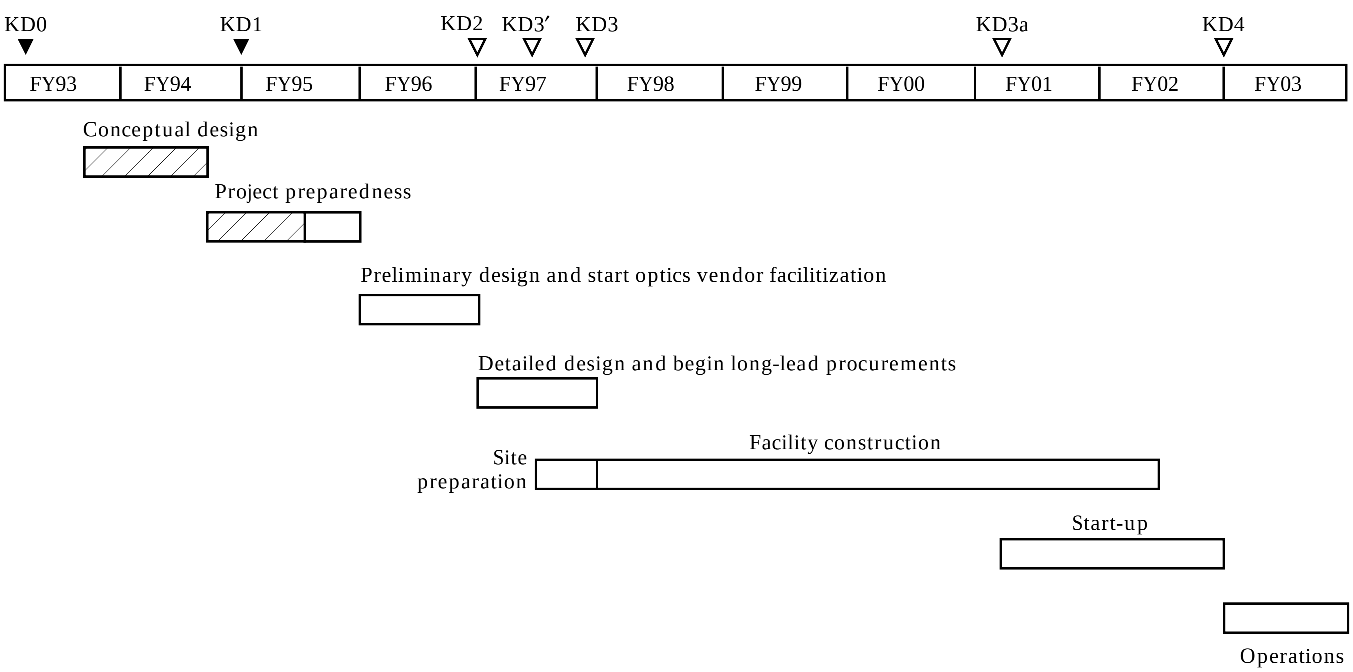


FIGURE 9. NIF Project schedule (hash marks and solid triangles indicate completion). (40-00-0195-0269Hpb01)

NIF Project Cost

The NIF Total Project Cost (TPC) is the sum of the Total Estimated Cost (TEC) and the Other Project Cost (OPC). The TEC is funded by Plant and Capital Equipment (PACE) funds and the OPC is funded by Operating Expense (OPEX) funds. Division of costs between TEC and OPC is provided in DOE guidelines. TEC activities include, for example, Title I and II design, and Title III engineering; building construction; procurement; assembly and installation of all special equipment; and sufficient spares to pass the acceptance test procedures. OPC activities include, for example, conceptual design; advanced conceptual design; NEPA documentation; vendor facilitization and pilot production; vendor component qualification / reliability / lifetime testing; operational readiness reviews; startup costs; and operational spares.

The costs shown in Table 3 were derived from a bottom-up estimate based on a detailed work breakdown structure (WBS) that is summarized at WBS Level 3 in Fig. 10. The Project adopted the Martin Marietta Energy Systems, Inc. Automated Estimating System (AES) as its cost management tool. The AES is consistent with DOE Order 5700.2d, “Cost Estimating Analysis and Standardization,” and has been used in many other DOE projects in the past. The labor rates,

TABLE 3. Summary of NIF costs for 192-beam system, in millions of dollars.

	Base costs ($M FY94)	Contingency ($M FY94)	Total ($M FY94)	Total ($M escalated)
TEC	586	121	707	842
OPC	199	N / A	199	231
TPC	785	121	906	1073
Annual operating costs	57	N / A	57	N / A

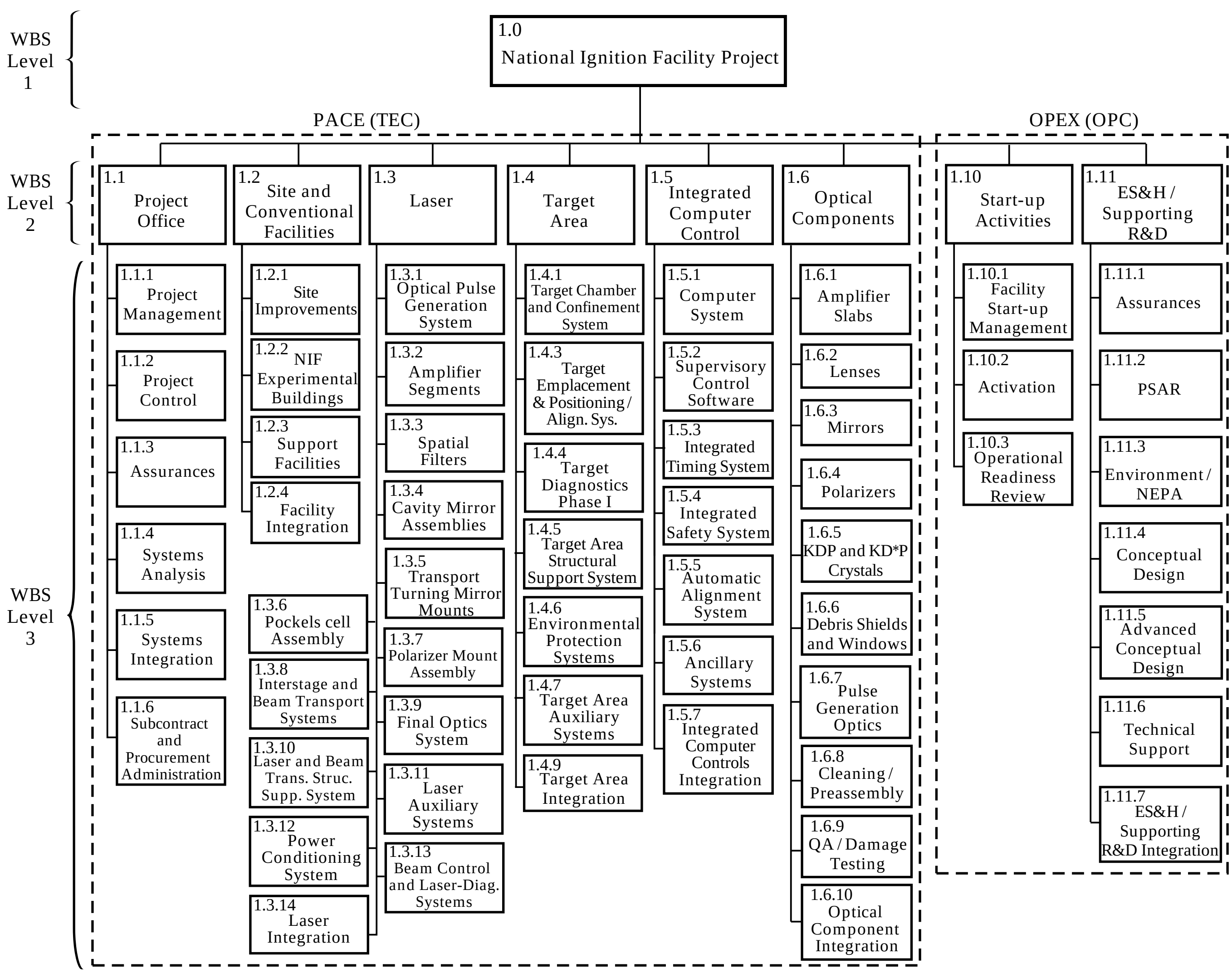
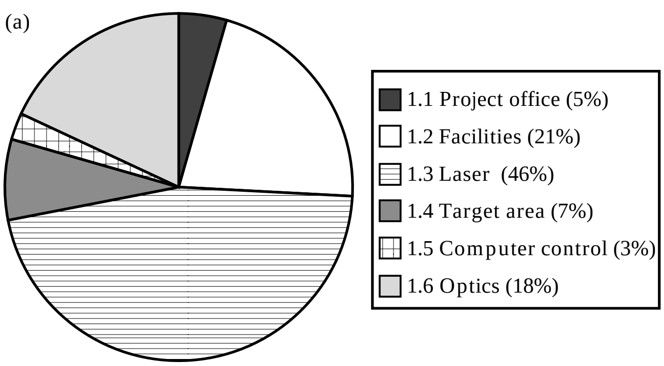


FIGURE 10. NIF Project WBS elements to Level 3. (1.4.0893.2859Mpb01)

overhead costs, allowances for incidental costs not directly estimated, and other indirect costs were applied to the database using the AES. Contingency information provided by each estimator for every Level 3 item was used in a separate probabilistic contingency analysis performed by Bechtel Corporation using their MICRORAC code. The results of that analysis were entered into the AES. Integrated project schedule data were combined with the cost information in the AES to estimate escalation and calculate the Budget Authority and Budget Outlay profiles required in the Project submission to DOE. The annual operating costs for the facility, shown in Table 3, were estimated by identifying all the NIF unit operations based on Nova experience. It does not include, per DOE guidance, the annual ICF Program costs (currently at approximately $175 million / yr).

Figure 11 gives a second-level breakout of TEC and a third-level breakout of OPC (without contingency or escalation). The engineering design was sufficiently detailed to generate costs, typically, at Level 5, and, in some cases, at Level 6 or 7. Approximately 70% of the costs (in dollars) were derived from catalog prices, vendor estimates, or engineering drawings. The costs in Table 2 have been validated by the DOE and by an Independent Cost Estimator team commissioned by DOE.

(a)



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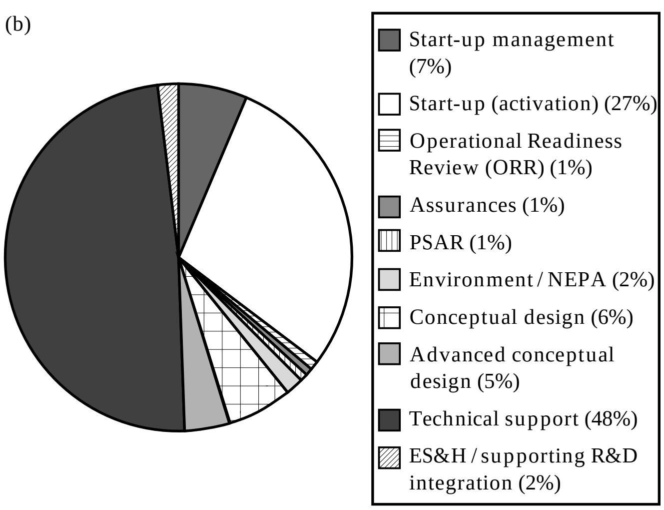

FIGURE 11. Cost breakouts for (a) TEC without contingency in unescalated dollars, broken down to Level 2 and for (b) OPC in unescalated dollars, broken down to Level 3. (40-00-0494-1720Apb01)

Summary

The NIF design is the product of the efforts of a multilaboratory team, representing more than 20 years of experience at the LLNL, LANL, SNL, and the Laboratory for Laser Energetics at the University of Rochester. Using the world's most powerful laser to ignite and burn ICF targets, the NIF will produce conditions in matter similar to those found at the center of the Sun and other stars. New, well characterized, high-energy-density regimes will be routinely accessible in the laboratory for the first time. The NIF will impact and extend scientific and technical fields such as controlled thermonuclear fusion, astrophysics and space science, plasma physics, hydrodynamics, atomic and radiation physics, material science, nonlinear optics, advanced coherent and incoherent x-ray sources, and computational physics. The importance and uniqueness of the NIF to these wide-ranging fields of science and technology have been recently reviewed in a series of workshops.[3] If authorized in FY 1996, the NIF could begin operations in FY 2003.

Notes and References

1. Committee for a Second Review of DOE's ICF Program, *Final Report—Second Review of the Department of Energy's Inertial Confinement Fusion Program*, National Academy of Sciences, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, National Academy Press, Washington, D.C. (September 1990).
2. J. A. Paisner, *National Ignition Facility Conceptual Design Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-PROP-117093 (1994).
3. J. A. Paisner, *Utility of the National Ignition Facility*, Lawrence Livermore National Laboratory, Livermore, CA, NIF-LLNL-94-240, UCRL-117384 (1994).